II

FOREIGN TECHNOLOGY CONCERNING FIRE SAFETY ASPECTS OF POLYMERIC MATERIALS

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ARMY MATERIEL COMMAND

US ARMY

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Introduction

The combustion of organic polymeric materials presents serious fire, smoke, and toxic vapor hazards. The growing use of these materials in all segments of our society has resulted in a heightened concern for the safety of human life and property. Scientific and technological solutions to the problem rest on improving present fire, smoke, and toxic vapor testing methods. This coupled with a fuller understanding of the dynamics of burning will lead to the development of organic materials that, as a result of composition and design, pose fewer and less severe combustion hazards. At this time, the technically advanced nations do not possess the necessary technology to accomplish this end. Nevertheless, these same countries realize the situation, and are striving to remedy it.

This paper presents the salient features of the foreign technology concerned with fire safety aspects of polymeric materials. It describes the current state of foreign test methods, of foreign contributions to the understanding of fire dynamics, and of foreign organic fire resistant polymers. Particular attention is paid to developments in the United Kingdom, France, West Germany, Japan, and the Soviet Union.

FIRE TEST METHODS

Background

Fire test methods are designed to provide information on the fire behavior of materials, and ideally are supposed to be a reliable basis for prediction of material behavior in an actual fire situation. Present foreign and domestic test methods have deficiencies which render them less than reliable in determining the fire properties of materials to define potential fire hazards. The inadequacies of fire test methods are many, and most technically advanced nations realize them and are attempting to develop new tests that exclude the shortcomings.

It is appropriate here to discuss some of the failings of present fire test methods. First of all, most tests were initially designed to be used for cellulosic materials, such as wood and cotton. With the advent of synthetic organic materials and their ever-expanding use in all phases of society, these tests are being employed for synthetics for which they may not be suitable. The design of the apparatus, the experimental conditions, and the criteria used for expressing results may need alteration from the original test specifications.

A second shortcoming is the reliance on small-scale laboratory testing to predict the behavior of a material in a full-scale fire situation. Small laboratory tests do not reproduce the massive heat effect of a full-scale fire, and thereby exclude a major factor that determines the spread of the fire, the damage to surrounding structures, and the hazard to life. A fire test should be designed with reference to a fire environment, and toward this end some large-scale test methods are being investigated by Canada and Great Britain. A test of the Canadian Standards Association is run on a final construction containing both the floor and ceiling assembly, while an American test, ASTM E-119, describes a large-scale wall test.

A further criticism is that when materials are tested alone but used in conjunction with other materials, the combined fire effect they have on one another is not measured in the performed test. A test not only has to reflect a real fire, but also must relate to an actual application of an item.

A fourth deficiency is the confusion and the contradictory nature of terms such as "flameproof", "self-extinguishing", "non-burning", and so on. At first glance these properties appear unequivocal. Yet, they can mean different things according to whether the tests are British, American, German, or Japanese. For example, confusion exists over "flammability", which is defined by British test BS 4422 as the capacity of a material to burn and defined by ASTM E176-66 as subject to easy ignition and rapid flaming combustion. The term "combustibility" also is surrounded by contradictions as illustrated by the results of a world-wide survey by H. W. Emmons (1). An international group submitted samples of 24 "combustible" materials to six European countries for rating by their national standard fire tests. Each county arranged the materials in order of combustibility. The lack of agreement is apparent when the results are examined (Table 1).

Table 1. Partial Listing of the Relative Rating of 24 Materials by Six Different National Standard Fire Rating Tests. The rating of 1 corresponds to most combustile, and 24 to least combustible.(1)

Material	W. Germany	Belgium	Denmark	France	Netherlands	UK
wood wool/cement slab	18	23.5	23	24	24	24
phenolic foam	24	23.5	1	21	19	19
expanded polystyrene	15	1	4	17	21	1
acrylic sheet	3	2	22	1	7	22

A fifth inadequacy of present fire test methods is the lack of reliable smoke tests and toxic vapor tests. There are some standardized smoke tests in West Germany, Netherlands, and the United States, but these methods define only a few conditions. Furthermore, there are no standard toxic vapor tests (under fire conditions) in the whole world. Tests have been proposed and carried out, however, that show toxic hazards of burning plastics on animals. The seriousness of the test inadequacies comes to light since the products of combustion, smoke, and toxic vapors appear to be the major causes of death in fires. This is supported by a study by Dr. A. W. Phillips (2) of the National Commission on Fire Prevention and Control (NCFPC). Phillips claims that 53% of victims succumbing in a fire die from inhaling smoke and harmful gases.

As was stated earlier, fire tests are designed to provide information on the fire behavior of materials. Fire behavior of polymeric materials can be characterized by six factors:

1. ignitability - or ease of ignition, defined as the ease with which a material is ignited under specificed conditions.

2. surface flame spread - defined as the rate of travel of a flame front under specific burning conditions. Some measures of flame spread are burning rate, flame spread factor, burning extent, and flame height.

3. fire resistance - defined as the resistance offered by the material to the passage of fire normal to the exposed surface over which the flame spread is measured.

4. heat release (fuel contribution) - defined as the heat produced by the combustion of a given weight of material.

5. smoke density - defined as the degree of light or sight obscuration produced by smoke from a burning material under given conditions.

6. toxic products - combustion products such as smoke and volatile gases.

Some of the foreign tests and standards that attempt to define the properties of organic materials are presented. Special attention is given to tests for smoke and toxic vapor production in subsequent sections.

United Kingdom

The Fire Research Station, the Greater London Council, and the UK Agreement Board are involved in fire tests and set appropriate standards for building materials. RAPRA (Rubber and Plastics Research Association) also has been investigating the relevance of present fire tests methods. All these organizations realize the deficiencies and are attempting to overcome them.

A recent fire in a cabaret on the Isle of Man brings the inadequacy of present fire test methods and standards into focus (3). The roof of the structure consisted of a plastic called ORGOGLASS whose fire properties made it unsuitable for such an application. The manufacturer indicated this in its information sheet. Nevertheless the material was used because the fire safety officer was not aware of its limitations. The point is that data on fire properties of materials are not easily accessible to those who need to have them. Although the Fire Research Station has tested over 4000 materials, these tests were paid for by the manufacturers and the results are not available to users. The same is true for the 300 tests performed by the Greater London Council. To circumvent this situation the British government set up the UK Agreement Board whose responsibility was to assess the performance of building materials and make the results public. However, use of the board by manufacturers, who by the way pay for the tests, is voluntary. Only 200 materials have so far been approved by this UK Board. The contrast should be drawn here between an analogous French Agreement Board which has approved over 4000 materials since 1963 for use in the building industry. Use of the French Board is obligatory and results are publicized. Consequently, critics argue that an easily accessible "handbook" is needed that clearly states the results of fire tests and describes the dangers and application restrictions of all new materials.

British Standard Test BS 476 consists of various parts, and in totality is used for evaluating building materials (4). BS 476 was revised in the past few years and has the following parts (5, 6):

Part 3. External Fire Exposure Roof Tests

Part 4. Non-combustibility Test for Materials

Part 5. Ignitability Test for Materials

Part 6. Fire Propagation Test for Materials

Part 7. Surface Spread of Flame Test for Materials

Part 8. Fire Resistance Tests for Elements of Building Construction

Part 9. (proposed) Smoke Density Test for Building Materials

The Ignitability Test for Materials (BS 476: Part 5) consists of applying a small flame to the surface of a vertically held sample. The test is similar to BS 4422: Part 2. Analogous foreign tests involve different orientations of the specimen and other heat sources. Consequently, comparative evaluations of ignitability show contradictions. The analogous American test for ignitability is ASTM D-1929.

The Fire Propagation Test (BS 476: Part 6) measures the heat contributed to the fire by the test material. It gives an indication of the pattern of heat evolution when a sample burns: (a) when exposed to a standard flame, and (b) when exposed to a standard flame and radiant heat. Materials are graded with respect to amount and rate of heat evolved, and an overall Fire Propagation Index is calculated by adding together three measured indices (7, 8).

- i_1, representing the early stages of ignition
- i_2, representing the growth to a fully developed fire
- i_3, representing the terminal stage of the fire

These indices are derived from measured temperature-time curves. Most foreign nations have similar tests, although they may differ in design details, and use a similar apparatus consisting of a "combustion box" provided with a controlled heat source. The British apparatus uses a multiple heat source and has an internal combustion chamber of 190mm x 190mm x 90mm (7).

BS 476: Part 7, the Surface Spread of Flame Test, has two versions (7). A preliminary (BS 476: Part 1) which is less severe, and the full scale which is the only version accepted by industry. In the full scale test the spread of flame is measured along a 300mm x 75 mm sample held in position at right angles to a 300mm, gas heated, square, radiant panel. The edge of the sample nearest to the panel is heated to 500°C. The test provides a means of assessing the tendency of a fire to spread through a building by travelling across the surfaces of combustible materials that have been preheated by radiation from the advancing fire. Four class ratings of materials are determined:

Class	Flame Spread at 1.5 min(cm)	Flame Spread at 10 min(cm)	Final Flame Spread(cm)
1	-	-	19
2	30	-	60
3	30	83	83
4	30	83	83

Building materials require class 1 or 2 ratings. Asbestos reinforced poly(vinyl chloride), and some glass-reinforced polyester and melamine laminates are rated class 1. In the United States, Underwriter's Laboratory Tunnel Test (ULE48) would give analogous ratings of 20 to 50 for class 1 materials.

BS 476: Part 7 and Part 6 complement one another when rating building materials and are appropriate for evaluating aircraft, land transport, and ship materials.

BS 476: Part 8 specifies fire resistance of building materials and structures and is similar to tests in other countries (8). In this test, full-size representative samples are exposed to standard heating conditions. The duration for which the criteria of stability, integrity, and insulation are satisfied is taken as the fire resistance of the specimen. International recommendation ISO R/834 also describes fire resistance testing for structures.

BS 476: Part 9 (Proposed) is a means of measuring smoke evolution in a fire (8). The test consists of performing the Fire Propagation Test (BS 476: Part 6) in a room of known volume equipped with two mixing fans of a specified air flow. The smoke density of flaming materials is calculated from observations of the obscuration of a light source across the center of the room. The percent obscuration (specific optical density) of the combustion products is then measured along with the rate of production.

Textile testing in the UK includes two standard methods BS 2963 and BS 4569 (revised in 1970) (9). The former is a vertical test method that is not suitable for napped fabrics. While the latter is an improved test in which the flame source is moved back and forth over the specimen to initiate ignition. BS 4569 is suitable for napped fabrics and is entitled "The Surface Flash in Pile Fabrics Test".

A combustibility test, BS 2782-508A, involves applying a flame for 10 seconds to a clamped specimen (9). The material is rated "self-extinguisning" if the burn does not reach 1 inch and the specimen burns for less than 5 seconds after flame removal. American test ASTM D-63572 is analogous except that the flame is applied for 30 seconds and the self-extinguishing ratings are different. According to the ASTM test if a specimen does not burn more than 3 seconds it is classed as "zero burning". If the burn does not exceed 4 inches then it is "self-extinguishing".

A Canadian standard put out by the Canadian Standards Association, designated CSA B54.3, defines fire tests for walls, partitions, floors, roofs, and ceilings (10).

An Australian standard that describes methods for fire tests on building materials and structures is designated by SAA A30 (10).

West Germany

In the Federal Republic of Germany many institutes are concerned with fire test methods for materials. Some of the facilities are: the Otto Graf Institute, Stuttgart; the Institute of Wood Research at the University of

Munich; the Research Station for Fire Protection at the University of Karlsruhe; the Federal Institute of Material Testing, Berlin; the Material Testing Council, Dortmund; and the Institute for Plastic Processing, Aachen. The last two facilities appear to be the key centers for research activities in test methods.

German industrial standard DIN 4102 is analogous to BS 476 in that they both define the fire test methods and classification of plastics and other building structures (7). The German standard consists of Parts 1 to 5, and classifies building materials according to combustibility. As of August 1972, complete specifications were not available for Parts 1 and 5. This German specification, however, includes testing of samples in a closed room (combustion shaft) at temperatures between 500-1000°C.

The testing of plastic floors is specified by DIN 51,961 and includes two tests (9). Test A involves placing a burning cigarette on a 100mm x 100mm sample and determining the time the plastic glows along a 40mm path. Test B measures changes and depth of burning after a burn time of 12 minutes when a cigarette is placed on a 200mm x 100mm specimen. Other building material tests are DIN 53,799, a test of laminated plastic slabs, and DIN 53,482 for testing the fire resistance of foils (7,9).

West Germany has standard tests for textiles as well (9). The "Test of the Burning Behavior of Textiles, Ideas and Applications" (DIN 54,330), which was in draft form in 1971, is claimed to represent an advancement in the establishment of unequivocal terms to define textile fire behavior properties, such as: noncombustible, hard to burn, combustible, easily burnable, after glow, ignitability, rate of flame propagation, and melting. The specification enphasizes the avoidance of confusing terms like "not-flammable" and "difficulty flammable".

German specification DIN 54,331, "The Determination of the Burning Behavior of Burnable Textiles, by the Arc-test Process", defines a test employing a burn box of 700mm x 390mm x 660 mm. The test measures burn-time, length of burn, and glow-period. The burn box for DIN 54,331 is also used in test specifications, such as:

DIN 53,906 - New Vertical Test Method

53,907 - New Horizontal Test Method

53,333 - The Flame Propagation Rate Test

54,334 - Ignition Time Test

54,332 - Test for the Combustibility of Textiles

Sweden

Combustibility tests are coordinated by the Swedish Institute for Building Research, Swedish Plastics Federation Division of Plastics in Building, and the Swedish Institute for Materiel Testing.

The Swedish "Hot-Box Test" (5, 9) is analogous to the British Fire Propagation Test (BS 476. Part 6). The Swedish test uses a single gas flame as heat source in a 300mm x 235mm x 235mm chamber. The rate and amount of heat evolution is measured from the obtained time-temperature curves. This "hot-box" is also used in a test for smoke density and rate of smoke evolution.

The Swedish Institute for Material Testing developed a test method for determining the combustibility of carpets under specification SP Br6 (9). A 40cm x 100cm sample is ignited in a tunnel with air velocity regulated at 2 meters per second. The test consists of determining the extent of damage along a 50cm long burn.

The Netherlands

The Fire Protection Center (TNO), in Delft, performs the fire tests of building materials (4). Chapter 3 of standard NEN 1076 describes combustibility tests and is similar to British Standard 476: Part 6, the Fire Propagation Test. The Dutch test is also characterized as the

"Flash Over Technique" in which two 300mm x 300mm specimens are exposed to radiating heat in such a way that they are separated by the heat source. One specimen is ignited by a gas flame, and the intensity of heat produced, that ignites the other sample, is measured.

Denmark

Danish fire standards are designated by DS notations and include: (1) DS 1057 defining fire classification of building of materials; (2) DS 1053, fire classification of doors; (3) DS 1052, fire classification of structures; and, (4) DS1051 describing fire resistance tests of structures (10).

Switzerland

A Swiss standard, SNV 198,898 which was in draft status in 1971, describes the determination of burn and glow periods of "difficultly combustible" textiles (9). The test is based on German standard DIN 53906 and American test AATCC-Test Method 34-1969. The Swiss test, however, does not include the effect of glass fibers on the fire properties, as do the German and American tests.

A testing apparatus, developed by the A. Hitz, Ahiba Company and designated FT70A, is claimed to be a versatile instrument in determining the flame propagation rates of textiles (9,11). The device allows specimens to be tested in specific positions, each varying with respect to the horizontal plane. According to the company, this advantageous feature may enable the apparatus to get international recognition and consequently may bring universal fire test methods for textiles a step closer to reality.

France

A French fire test developed by the Fire Safety Center measures an "ignition index", a "flame propagation index", a "maximum flame height index", and a "combustibility index". The test was modified in 1965 under designation 57-1161. The test involves exposing a 300mm x 400mm specimen to radiating heat. Building materials are categorized as follows:

Class 1 - incombustible, if the values of the igniting flame propagation and maximum flame height indices are zero.

Class 2 - hardly combustible, if the value of all indices is less than 1.

Class 3 - moderately combustible, if the ignition index is less than 2, and the combustion index is greater than 2.5

Class 4 - easily combustible, if none of the requirements of the first three classes can be met.

Japan

In Japan, the government has the authority to control industrial standards and uses the JIS-mark indication system. Japan is implementing international cooperation in establishing industrial standards. The Japanese are increasing their participation in the International Organization of Standards (ISO), and are attempting to make their JIS widely available to producers, distributors, users, and consumers of industrial products in Japan and in other countries (12).

Japan's growing concern with present fire test methods and standards is also apparent. In 1972, they expressed a desire to legislate non-flammable quality certification for all textiles and proposed a law setting safeguard fire standards in apartment houses and entertainment establishments (9).

The specification JIS L 1009-1966 describes three fire test methods for textiles (9). The standard is based on American test methods AATCC 33-1966 and AATCC 34-1969. Besides textile testing, a series of test methods exists for the determination of combustibility of building materials. Standard JIS K 5661 describes specifications of fire retardant paints for buildings (10).

USSR

In the Soviet Union, the Central Fire-Fighting Research Institute (ZNIIPO), in Moscow, is concerned with the problems of combustible materials. The amount of heat released during combustion is taken as a basis for classifying building materials as combustible. This differs from tests other countries use to determine combustibility. The test involves burning a 35mm x 75mm x 10mm specimen in a calorimeter. The quotient of the quantity of heat developing during burning and the quantity of heat delivered by the flame source is the "K value" and is the basis of classification. Ratings are based on the following "K values":

$K < 0.1$	- incombustible
$0.1 < K < 0.5$	- hardly combustible
$0.5 < K < 2.1$	- hardly flammable
$2.1 < K$	- easily flammable

Hungary

In Hungary, the fire behavior properties of building materials are investigated at the Fire Resistance Laboratory of the Institute for the Quality Control of Building. The Research Institute for the Plastics Industry and the Fire-Fighting Department of the Ministry of the Interior are also concerned with testing the combustibility of plastics.

The combustibility and fire resistance tests of building materials are specified by a series of standards designated MSz 14,800. Only 3 of the 12 proposed standards had been published as of 1972. These standards eventually will coordinate all test methods for building materials. Standard MSz 14,800/3 is based on the German standard DIN 4102 that defines combustibility.

Limited Oxygen Index Method

The Limited Oxygen Index Test, although initially developed at the General Electric Company, is receiving increased international recognition as a sensitive and reproducible technique for measuring a fundamental property of a material. The test (ASTM D2863-70) consists of adjusting the proportions of oxygen and nitrogen until a specimen burns for either a distance of 50mm or a time of 3 minutes (8). An Oxygen Index rating is determined, defining the lowest concentration of oxygen necessary for a material to burn under the above specifications. The test is small scale and may not always be relevant in describing the practical fire behavior of materials. The test, however, is used by the UK (8), Hungary (13), the USSR (14), Japan (15), and other European nations (16).

SMOKE TESTS

The toxicology of all fires consists of features, such as heat, oxygen deficiency, carbon monoxide and other gases, smoke, and panic or emotional shock. In the case of burning organic materials, however, the evolution of various toxic gases and dense smoke appears to be unique. Unfortunately less than reliable test methods exist for these products, despite the fact that they products present the greatest hazard to life in a real fire.

Smoke not only presents toxic hazards, but also can prevent escape from fires by obscuring vision. Smoke evolution in a fire is less reliably measured compared to heat release, ignitability, fire resistance, and flame spread (17, 18). There are a few American tests that attempt to define and measure smoke evolution (19). The Steiner Tunnel Test (ASTM E-84) is a large-scale test for smoke density. While small-scale tests include the Rohm and Haas XP-2 test (ASTM 2843- 70) and the National Bureau of Standards Smoke Chamber Test. The XP-2 test is claimed to correlate well with large-scale burning tests done outdoors. The NBS Smoke Chamber test employs a closed cabinet having a volume of 18 cubic feet. A 3-inch square specimen is exposed to heat under flaming or nonflaming conditions. Light absorption is measured vertically to minimize differences caused by stratification of the smoke. The test measures specific optical density, maximum smoke accumulation, maximum smoke accumulation rate, and time to reach maximum smoke density.

The ability of small-scale tests to predict smoke production in large fires was studied by the IIT Research Institute for the Society of the Plastics Industry in 1966 (19, 20). It was found that in the case of smoke hazards of interior finish materials, the data on smoke production are not adequately defined by a smoke rating number from a single small-scale test. The inadequacies appear to result from an inability to produce the extremely heavy smoke associated with total fires. Consequently, the study concluded that improved methods must be devised to predict smoke evolution. This assertion holds as true in 1973 as it did in 1966.

Foreign nations have recognized the problem and some of the technically advanced countries, such as the United Kingdom, the Netherlands, West Germany, and Switzerland, are conducting research to improve test methods to eventually lead to the control of smoke.

United Kingdom

In the United Kingdom, research at the Fire Research Station has led to the development of a smoke chamber measuring 3.6m x 3.36m x 2.79m (21). This chamber probably is the basis for Part 9 of BS 476 that was in "proposed" status in 1972. A schematic shows the apparatus (fig. 1).

British Smoke Chamber

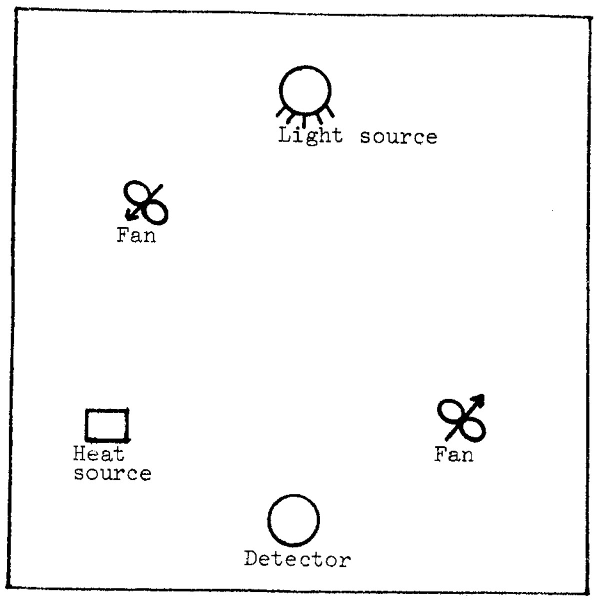

Figure 1

The test is designed to establish the smoke levels in escape corridors, which are adjacent to the room containing the burning material. Consequently, the test can predict the hazard that might prevent escape of persons from these adjoining rooms and corridors.

In February 1973, the Stanton Redcraft Company reported the marketing of an apparatus that they claim can effectively measure smoke and other flammability characteristics (22). The equipment consists of "Module FTA" (the critical oxygen index test apparatus) and "Module FTB"(the smoke density box). The firm claims the set-up can measure (1) flammability as expressed by the Critical Oxygen Index (COI), (2) smoke density, (3) temperature of burning, rate of burning, burning profile, after glow, and (4) formation and analysis of evolved gases. It appears that Stanton Redcraft has the proverbial "magic black box". Nevertheless, their claims have yet to be substantiated.

At the Queen Mary College conference on burning plastics in February 1973, British scientists reported that the scanning electron microscope (SEM) was useful in learning about smoke (23). In one example, smoke had been trapped in a water tank and examined on the surface of a grid showing it to consist of a carbon skeleton with crystalline inclusions. Although not reported yet, it is claimed that research into the char structure of flame retardant foams and other plastics might be possible by the use of the SEM.

The Netherlands

A Dutch smoke measurement apparatus is illustrated schematically (fig. 2) (21).

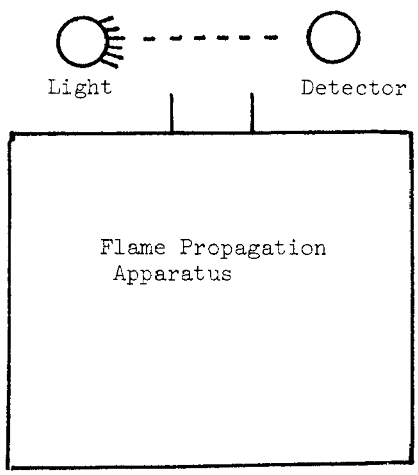

Figure 2.

The test is characterized by thermal decomposition from radiating heat. Smoke is liberated into the open air, and measurements are taken over the point of exit.

West Germany

German Standard DIN 53,436 (Draft as of 1972) describes an "Apparatus for the Thermal Decomposition of Plastics under Air Flow (5 liters/min)". The equipment is represented schematically (fig. 3) (21).

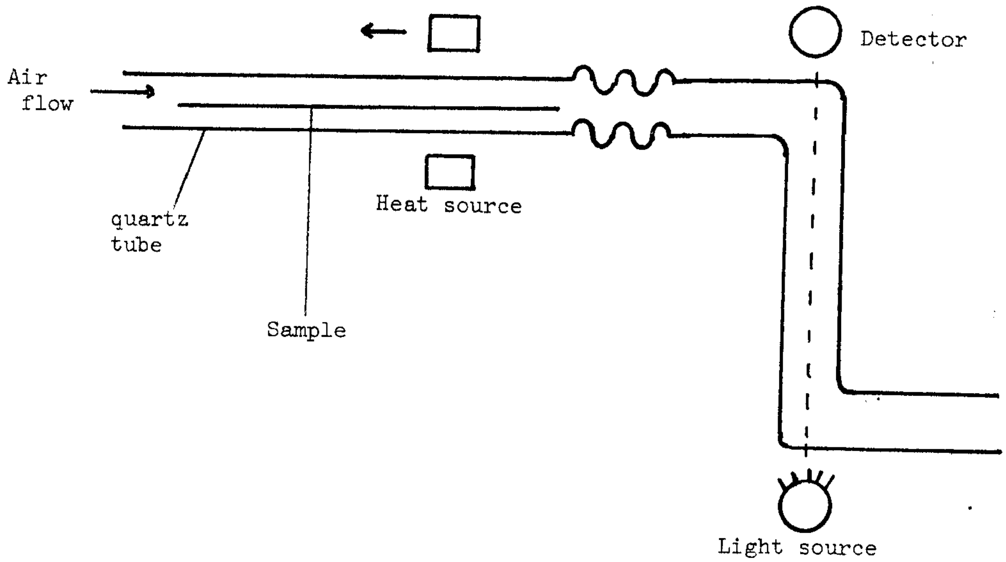

Figure 3.

The samples are burned in a 1 meter long quartz tube. The oven with a variable heat output is moved across the tube at 10 mm/minute, burning the material at a fixed rate. Air flow is maintained at 5 l/minute. Samples measure 1000mm x 15mm x 2mm.

In Switzerland and Sweden research also is underway in smoke density measurements. Nevertheless, there are no countries in the world that have a test that can reliably predict smoke generation under the myriad possible conditions associated with a real fire.

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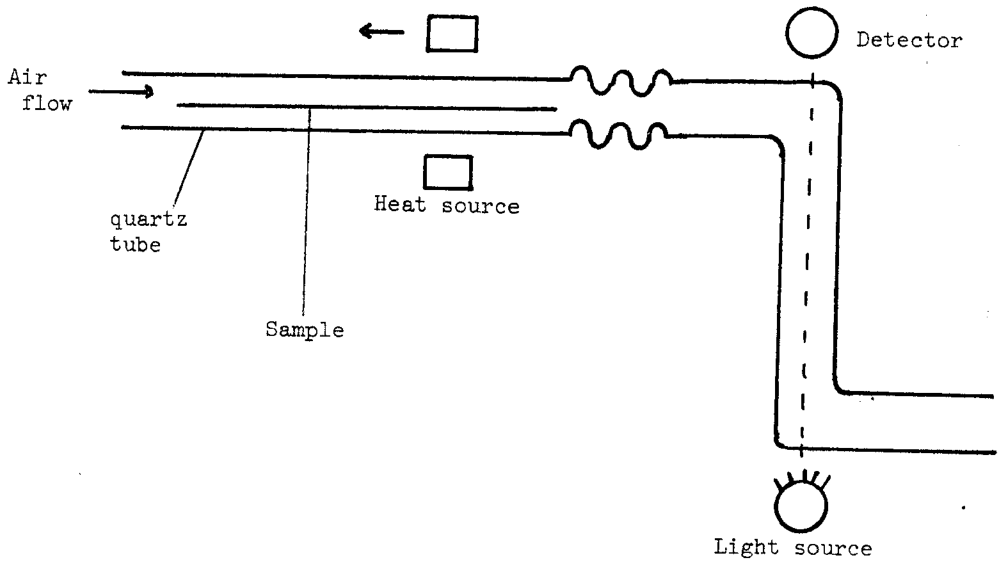

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In Canada, a technique has been developed for determining the "toxic potential" of materials (5). A known amount of a sample is decomposed at 900°C and the concentrations of poisonous gases are measured. These concentrations are related to the minimum lethal levels and are expressed as the toxicity potential. No synergistic effects are assumed in this test however.

American researchers, such as Boettner and Ball at the University of Michigan, Einhorn at the University of Utah, and Pryor at the Southwest Research Institute, San Antonio, also are actively pursuing the toxicological effects of combustion products from burning plastics (25).

In the United Kingdom, research at the Fire Research Station has involved the use of sophisticated spectrographic techniques to study the range of products from burning polymers (5). Researchers also intend to study the synergistic aspects of these products. According to H. L. Malhorta of the FRS, referring to the toxic vapor problem,"it is likely to be about five years before sufficient data become available to permit decisions to be taken on the likely hazards, methods of assessment, and methods of control."

Interesting work in this area is going on in West Germany (26). A proposed test defines conditions in which small specimens are decomposed at various temperatures. The toxicity of the combustion products then is determined by exposing mice to the resulting atmosphere. This test may be based on the work done by H. Oettel (26) of BASF (Badische-Anilin und Soda Fabrick), who determined the toxic effects of burning materials by measuring the percent of carbon monoxide-hemoglobin in the blood of exposed rats.

Effenberger (26) also has contributed to the solution of the problem. His work has involved exposing rats to the toxic environment of burning plastics. The apparatus described by DIN 53,436 (Draft) was attached to a plexiglas container into which the rats were placed. Five exhaust lines went into the tank. The time of exposure was 100 minutes. The criteria used to interpret the results were (1) comparison of the number of surviving rats to dead ones (Table 2), and (2) the content of carbon monoxide-hemoglobin in the blood(Table 3).

Table 2. Acute Death of Rats under the Influence of Combustion Products of Materials.

Material	Number of Rats	Number Dead	Number Unharmed
Pine wood	14	11	3
Wool fabric	9	0	9
Polystyrene	29	0	29
Laminated plastic	10	0	10
Melamine resin	17	2	15
Polyester cloth	9	0	9
Polyacrylonitrile	14	13	1
Polyurethane	20	2	18

Table 3. Average COHb - Content in the Blood of Rats Exposed to the Combustion Products of Materials

Material	Number of Rats	Average COHb Content in the blood
Pine wood	11	66.1
Wool fabric	7	32.4
Polystyrene	7	3.2
Laminated plastic	6	42.7
Melamine resin	6	33.7
Polyester fabric	5	19.2
Polyacrylonitrile	8	3.0
Polyurethane foam	20	24.6

The results show that pine wood and polyacrylonitrile produced the greatest fatalities. Yet the carbon monoxide content in the blood of rats exposed to burning pine wood was twenty times that of the blood of rats exposed to burning polyacrylonitrile. In the latter case, hydrogen cyanide and ammonia gas are probably the major lethal gases.

Effenberger realized that these two tests did not take into account the more subtle effects of toxic gases. That is to say, the effect of the poisons in lowering mobility and thereby reducing the ability of the rats to try to escape. Therefore, he devised a "swimtest", which consisted of exposing rats to the combustion products of the same materials as before. Here, however, results were interpreted by determining the time each rat remained afloat and swimming before drowning (Table 4).

Table 4. Results of "Swim test".

Material	Number of Rats	Average Swim time (minutes)
Pine wood	7	4.0
Wool fabric	9	6.9
Polystyrene	23	1.3
Laminates	6	180.8
Melamine resins	8	84.2
Polyester fabric	14	79.0
Polyacrylonitrile	22	8.1
Polyurethane foam	11	55.3

The startling results show that burning polystyrene, which produced no dead rats in the other experiments and resulted in a very low carbon monoxide content, caused the shortest swim-time resulting in death by drowning. The unique burning product evolved, other than carbon monoxide, is styrene which apparently has an immobilizing effect on the rat. This interpretation may be extended to fires involving humans, in which death may be imminent because the ability to escape from the fire is impaired.

In Japan, work done at the University of Tokyo, in 1971, also involved exposing mice to the toxic environment of burning materials (27). Exposure time was 15 minutes and pyrolysis temperatures were near 790°C. Results were interpreted by comparing mortality rates due to exposure to the respective burning samples.

With the increased use of organic materials has come a growing awareness in the toxicology of combustion products. Unfortunately, standardized tests that involve biological evaluation of degradation products are not available at present, although tests do exist. The problem is realized in the technically advanced nations, and test procedures have been proposed for standardization in some of these countries.

DYNAMICS OF FIRE

Current Theory

The study of the burning processes of materials is geared to a better understanding of dynamic aspects, such as ignition, flame propagation (or spread), and thermal decomposition, so that new materials may be developed that, as a result of composition and design, will have reduced fire hazards. A review by Einhorn (25), at the University of Utah, presents a detailed picture of the mechanism of combustion of materials. A brief summary is presented here, and some of the contributions of foreign scientists to the study of flame propagation follows.

According to Einhorn, a material burns in several stages (fig. 4). An external heat source (flaming, non-flaming, or electrical) is applied to a material. This source may also introduce free-radical species and cause the material to react further by liberating gases or combining with oxygen. These two processes increase the temperature of the material until the decomposition temperature is reached (stage 2). In this stage, combustible gases, noncombustible gases, liquids, carbonaceous residue, and smoke are produced. The combustible gases in turn are oxidized, regenerating additional heat. Carbonaceous residues (or char) are desirable because they preserve structural integrity, retard the outward flow of combustible gases, prevent mixing of air with these gases, and insulate the material from heat that might cause further degradation. This attribute of char is the basis for the fire retardant character of intumescent coatings and some insulating foams.

Dynamics of Burning Materials

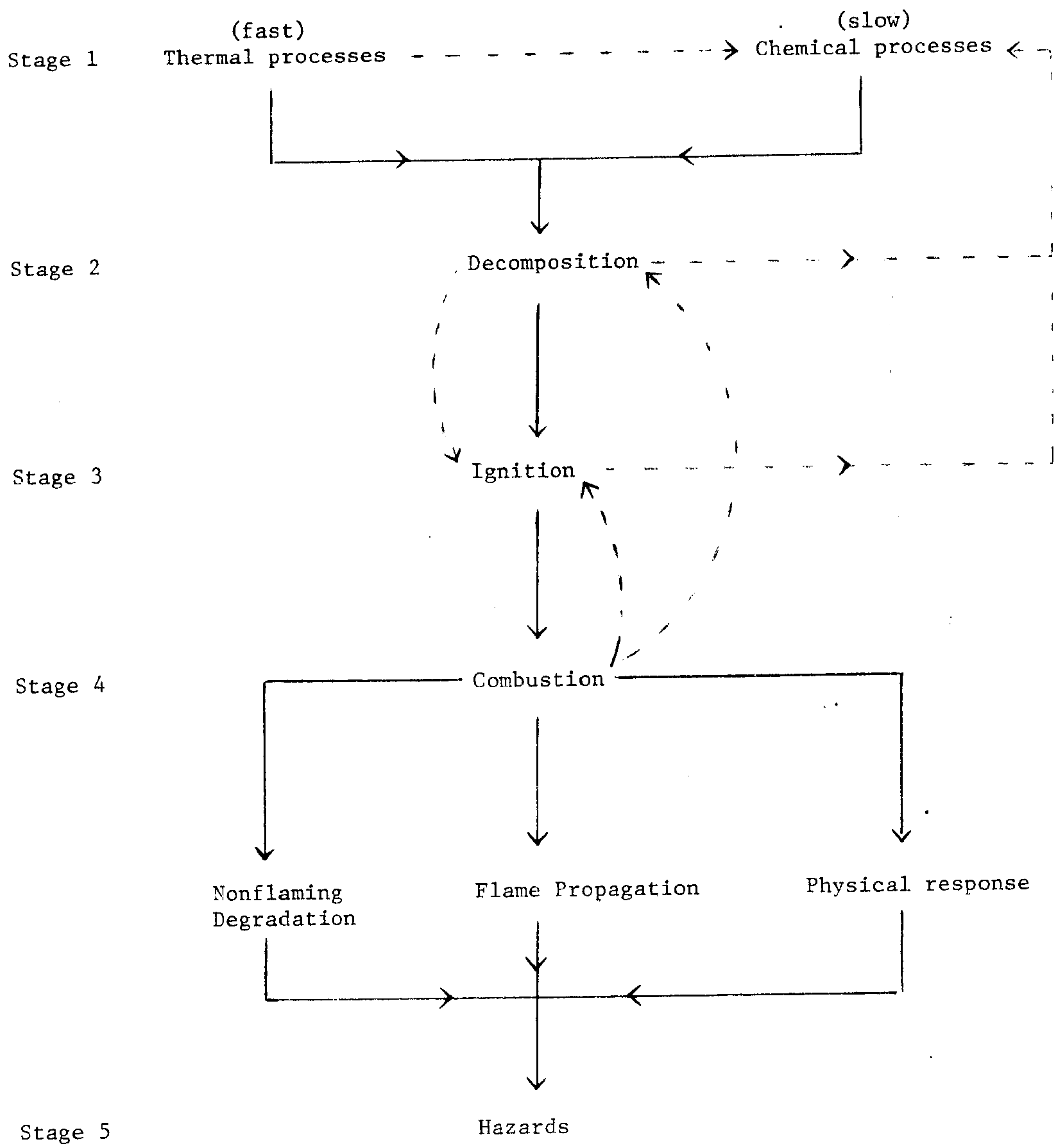

Figure 4.

Stage 3 involves ignition of combustible gases in the presence of sufficient oxidizing agents, in maintaining a self-sustaining reaction within the material. Stage 4 is based on the potential energy within the material, which includes cohesive energy, hydrogen bonding, heat of combustion, and bond dissociation energy. If the net thermal effect of combustion is negative, an external supply of heat is necessary to support burning. In such a case removal of the heat source may result in self-extinction of the fire. If the net thermal effect is positive, the heat excess feeds the fire by increasing the temperature of adjacent material which in turn decomposes and passes from Stage 2 to 3 and so on.

The stage of combustion includes three possible paths: (1) nonflaming degradation, (2) flame propagation, and (3) physical response (shielding, charring, melting). Flame propagation occurs when the net heat of combustion is sufficient to bring the adjacent mass to the burning stage. This depends on the structure and design of the material.

Stages 1 through 4 lead to Stage 5, which is the hazards of the fire, such as heat, smoke, toxic gases, and so on. As previously stated, it is these hazards that fire test methods are designed to evaluate.

Fire Propagation Studies

Scientists at the Spanish Aerospace Institute, Madrid, have made significant contributions to the theory of surface flame propagation (or spread) (28). Their work has led to correlations between theoretical and experimental results, and is similar to American views as espoused by Magee and McAlevy (29, 30) of the Stevens Institute of Technology. According to both research groups, the principal exothermic reaction occurs in the gas phase between volatile combustibles diffusing away from the surface and oxygen going toward it. At a surface location in advance of the flame front, heat from the front causes pyrolysis. The vapors that evolve diffuse away from the surface and are oxidized liberating heat that is fed back to the surface. Taken together, the heat from the advancing flames and the heat fed back from the reaction zone accelerate the vaporization of combustibles and their gas-phase oxidation. This occurrence raises the temperature to the ignition point as the glame front reaches the surface location.

This theory, however, excludes any events that occur in the solid phase. In some cases pyrolysis of the solid phase is significant. Japanese workers (31, 32) have studied the reactions in the condensed phase and have supported the claim that pyrolysis involves the formation of two zones: a pyrolysis zone, which moves into the solid away from the surface as the material is vaporized, and a char zone between the surface and the pyrolysis zone. Primary degradation occurs in the pyrolysis zone. Secondary burning will occur in the char zone if oxygen can enter it and participate in exothermic reactions with combustible vapors or char surfaces.

Recent studies into flame spread phenomena include the work of Mizutani (33) at Osaka University. Here attempts were made to examine the mutual effects between a flame and the aerodynamics (or turbulence). The existence of turbulence increases the flame velocity, while the flame augments the intensity of turbulence. A series of equations for calculating turbulent flame velocities over a wide range of conditions was proposed. These relationships are claimed to help clarify the interactions of flame and aerodynamics, and thereby provide some explanation of flame structure and propagation.

The study of turbulent flames also has been investigated at the Lotnictwa Institute, Warsaw (34). The workers applied chemiluminescent measurements in the study of the structure of turbulent flame. Although the use of chemiluminescence is not new in this endeavor, the workers propose that their techniques have removed the deficiencies of previous experiments. Their technique involves using a microphotometer that can measure local radiation inside the combustion region. Since the intensity of the local radiation is assumed to be proportional to the mass rate of chemical reaction at that point, measurement of this radiation may reveal the fine structure of flames. The effects of aerodynamics on turbulent flames also have been studied by Russian workers (35).